

Experimental analysis of microgenerators based on different prime movers

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ABSTRACT

The European Union recently established an ambitious target by 2020 that consists of increasing the utilization of renewable energy up to 20%, reducing its overall pollutant emissions by at least 20%, and achieving a primary energy saving of 20% compared to reported 1990 levels. This aim can only be realized with strong effort in different sectors, such as residential, commercial, industry, tertiary, transportation. In particular in the European Union, a remarkable contribution to energy consumption and CO₂ emissions is concentrated in residential and commercial sector. The introduction of more efficient technologies in these sectors could help in achieving the results expected by 2020. An option is given by cogeneration, defined as the combined “production” of electric and/or mechanical and thermal energy starting from single energy source. This technology could be considered one of the first elements to save primary energy, to avoid network losses and to reduce greenhouse gas emissions. In particular, this article focuses on the microcogeneration (electric power ≤ 15 kW), which represents a valid and interesting application for residential and light commercial users. The energy, economic and environmental implications due to the use of small scale cogeneration systems were reported, by means of an experimental research activity performed by the authors and other researchers.

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1. Introduction

Cogeneration, CHP (combined heat and power), the combined production of electric (and/or mechanical) and thermal energy, starting by a single primary energy source, is a well established technology, which has important benefits. It has been considered by the European Union [1], as one of the first elements to save primary energy and to reduce greenhouse gas emissions compared to the reference separate “production” by large thermal power stations and finally to avoid network losses. The “heart” of these energy conversion systems is a prime mover based on different technologies (Stirling, reciprocating internal combustion (RIC), fuel cell, gas turbine, Rankine cycle, . . .), especially designed to operate in stationary conditions for a long time with a high efficiency and very low pollutant emissions. At the moment, the most mature technology available in the market, gas-fired RIC engines, achieves small installation space, high thermal efficiency, reduction of noise and vibrations, low maintenance and long life service. In particular, the analysis will be focused on the microcogeneration, MCHP (micro-CHP), process (electric power output ≤ 15 kW), which represents a valid and interesting application suitable, above all, to residential and light commercial users [2].

In this paper the most important energy, economic and environmental impact performance indices of RIC and Stirling engine cogeneration systems have been evaluated and compared with those of conventional system, characterized by an electric and thermal separate “production” to supply the demands of the end-user.

2. Microcogeneration

At the moment, microgenerators, based on RIC and Stirling engines, are already available in the market and a large R&D activity aims at producing small commercially available units based on fuel cells, gas and steam turbines [3,4], in the medium and long period.

In this paper, the analysis will be focused only on the microcogenerators based on RIC and Stirling engines.

2.1. Microcogenerators based on reciprocating internal combustion engine

A lot of the current microcogenerators, based on RIC engines fuelled by natural gas, have been designed starting by small Gas engine driven Heat Pumps, GHP, that have been developed since 1979, in Japan, USA and in Europe [5]. This gas cooling technology

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Nomenclature

AS	Alternative System
CHP	Combined heat and power
CO ₂	Carbon dioxide equivalent emissions [kg]
CS	Conventional system
E	Energy [kWh]
$\dot{E}$	Power [kW]
GHP	Gas engine driven heat pump
LHV	Lower heating value [kWh/Nm ³]
MCHP	Micro combined heat and power
PER	Primary Energy Ratio [%]
PES	Primary energy saving [%]
PP	Power plant
RIC	Reciprocating internal combustion
Δ CO ₂	Equivalent CO ₂ avoided emissions [%]
η	Efficiency [%]

Subscripts

AS	Alternative System
B	Boiler
CS	Conventional system
MCHP	Micro combined heat and power
PP	Power plant
US	User
el	Electric
p	Primary
th	Thermal

is basically a heat activated heat pump in which a gas engine is used to drive the compressor of an inverse machine, ensuring a very high heating and cooling capacity. An MCHP could be derived by a GHP if the compressor is substituted by an electric generator. A lot of effort has been spent to develop new small displacement engine to stationary use and to allow the engine heat recovery, with a particular attention to the design of the exhaust gas heat exchanger, which is also the engine muffler. Some specifications were required:

- High efficiency: an appropriate combustion chamber was designed to achieve a rapid combustion and a reduction of frictional losses;
- Good durability: a forced oil circulation was employed for all engine surfaces together with the development of oil especially produced for gas engines. Furthermore, an appropriate choice of materials and valve seat angle, and an improvement of material quality, shape and surface treatment were made. In this way, the engine maintenance was optimized.

These engines occupy small installation space, have high mechanical (25–35%) and thermal (50–65%) efficiencies, low noise (<60 dB(A) at 1 m) and vibrations, low maintenance (one change of spark plugs and oil a year, corresponding to about 4000 h) and long life service (40,000–60,000 h, corresponding to about 10 years). Finally due to lean burn, NO_x emissions are less than 100 ppm with a stable shaft power output in a range of engine speed between 1200 and 3000 rpm.

A number of RIC engine based cogeneration systems, suitable for the residential sector, are currently available in the market.

Honda [6], and Osaka Gas have developed the Ecowill model [7]. This is a 1 kW electrical and 2.80 kW thermal output cogeneration unit, designed for single-family applications with an overall energy efficiency of 85%. In the period 2003–2009 about 86,000 units were sold in Japan with the introduction of a new model in the North

American market in 2006 capable of supplying 1.2 kW of electric power [8].

Tokyo Gas and Aisin (Toyota group), in February 2002, launched an MCHP [9,10], in Japan which has also been available in the European market since 2006. The model, based on a 3-cylinder-952 cm³ RIC engine, supplies an electric output of 6 kW and 11.7 kW of thermal power, with a total efficiency, at full load, equal to 85%.

The German manufacturer, Senertec [11], that has installed until now over 20,000 units in Europe, produces a cogeneration unit of 5.5 kW electric and 12.5 kW thermal power called Dachs. This unit is based on a one-cylinder four-stroke Sachs engine which has a displacement of 579 cm³ and can be fuelled by natural gas, LPG, fuel oil or biodiesel. The total efficiency at full load was lower than 90%. With an optional exhaust gas heat exchanger, the thermal output could be raised to 13.3 kW. The total efficiency then was 92% [12].

Finally PowerPlus Technologies [13], with the Ecopower module, proposes an MCHP, based on Briggs & Stratton 5HP engine, fuelled by natural gas or propane, of 4.7 kW electrical and 12.5 kW thermal outputs for an overall energy efficiency of up to 92%. The cogenerator can modulate the electric power between 2.0 kW (6.0 kW of thermal power) and 4.7 kW (12.5 kW of thermal power).

2.2. Microcogenerators based on Stirling engine

The Stirling engine was invented in 1816 by Robert Stirling in Scotland, but at the beginning of last century, due to the rapid development of internal combustion engines, these engines were partially abandoned [14]. This technology is based on an external combustion engine allowing the use of different primary energy sources including fossil fuels (oil or natural gas) and renewable energy sources (solar or biomass). In this engine, the working gas (helium, hydrogen, oxygen, nitrogen, carbon dioxide, etc.) operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working gas at different temperature levels.

The technology is not fully developed yet, and it is not widely used. However, there is an increasing interest in the use of small scale cogeneration systems based on Stirling engines because of their prospect for high global efficiency, good performance at partial load, fuel flexibility, low emission level, low vibration and noise level. Despite many advantages, the Stirling engine, with respect to RIC engine, has found few applications due to low electric efficiency, difficult power control system because of presence of different heat exchangers (heater, cooler, regenerator and auxiliary heat exchangers), high pressure level of working gas, high specific investment cost and finally the engine needs a few minutes to warm up.

Different small scale Stirling-based cogenerators are available in the market or under development.

A New Zealand company, Whisper Tech, offers since 1995 the Whispergen MCHP unit based on an Alpha-type 4-cylinder Stirling engine. The unit supplies an electric power of 1 kW and a thermal power of 12 kW. This MCHP is also currently being distributed in the UK by E. ON., a power and gas company. The unit can be fuelled by diesel oil, kerosene, natural gas, petrol.

SOLO Stirling started selling an MCHP unit in 2004 and by the beginning of 2007 about 150 units had been sold until the company went into insolvency in the same year. The units were designed for natural gas and LPG, but few units were modified to work with biogas, sewage gas, wood pellets and solar source [15]. SOLO MCHP is based on a 2-cylinder, 160 cm³, Alpha-type Stirling engine. Helium is used as working gas for the MCHP, while the solar based system uses hydrogen. The working gas pressure varies between 35 and 150 bar, providing a corresponding variable output of 2–9 kW electric and 8–26 kW thermal power.

A German manufacturer produced a cogeneration unit, called Sunmachine, of 3 kW electric and 10.5 kW thermal power based on

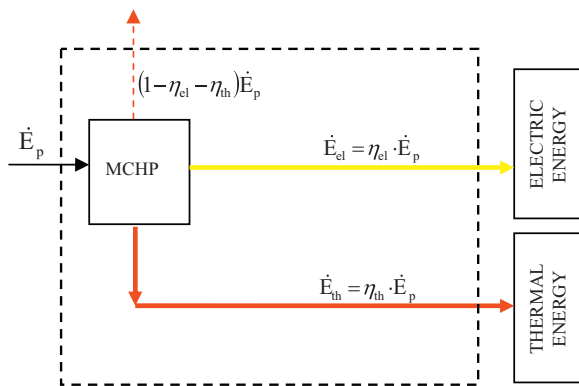


Fig. 1. Scheme of MCHP system.

Stirling engine powered by biogas, wood pellet and solar source. The Company, however, had to start insolvency proceedings due to technical problems.

Stirling Denmark, in cooperation with Danish Technical University, has developed the MCHP unit SM5A that is not yet available in the market. The cogenerator, based on a beta-type Stirling engine, delivers, at nominal condition, 8.1 kW of electric power and 24.9 kW of thermal power [16]. The unit uses helium as working gas and was developed for utilization of biogas.

In 2005, a Dutch company, ENATEC, entered into cooperation with boiler manufacturers to develop a natural gas-fired MCHP unit, HRe-boiler, that supplies 1 kW of electric power and 6.4 kW of thermal power.

Further MCHP units, based on Stirling engine, are still under development and will be available in the market within the next few years [3,4,17].

3. Experimental results on MCHP systems

From the main energy flows deducted by experimental research activity performed by the authors and other researchers, certain efficiencies are evaluated considering different operating modes. In Fig. 1, the main energy flows of the MCHP are reported.

In order to evaluate the electric efficiency of an MCHP, η_{el} , the ratio between electric power, $\dot{E}_{el}$, and primary input power, $\dot{E}_p$, is considered. Similarly the thermal efficiency, η_{th} , is evaluated as the ratio between thermal power, $\dot{E}_{th}$, and primary power input, $\dot{E}_p$. Finally, the global energy efficiency of MCHP is evaluated using the Primary Energy Ratio, PER, defined as the ratio of the useful power output (electric + thermal power) supplied to the end-user, to the primary input power.

The main characteristics of some small scale cogenerators, based on RIC engine, fuelled by natural gas available in the market are reported in Table 1. Here, it is evident that the models, considering the manufacturer's data, cover a large electric power range (1.0–13.0 kW), typical for a lot of users (from domestic to light commercial). The manufacturer's data on some Stirling engine-based cogenerators that are currently available in the market or those that are under development are reported in Table 2.

The most important thermodynamic properties have been experimentally analyzed to evaluate the energy flow rates of different cogenerators based on RIC and Stirling engines, as reported in Tables 1 and 2. In particular, the Aisin, Dachs, Ecopower and SOLO models have been tested by the authors [18–21], with further information obtained by scientific literature [22–29].

The MCHPs have been tested in a wide range of working conditions varying both electric and thermal power supplied to the end-user, as shown in Fig. 2 for each MCHP. It is important to underline that Dachs and Ecowill cogenerator do not work at partial load.

Table 1
MCHP systems with internal combustion engine available on market and their specification.

	1. Honda Ecowill	2. Aisin Seiki GECC 46 A2	3. Ecopower e4.7	4. Senertec Dachs HKA G	5. Yanmar CP5VB	6. Senertec Dachs HKA H	7. Senertec Dachs HKA G	8. Aisin Seiki GECC 60 A2	9. Yanmar CP10VB1	10. Ecogen-12AG	11. Ecopower XRG113 NGAS
Power [kW]	4.4	18.0	18.9	19.6	17.2	17.6	20.5	20.8	31.4	31.4	46.4
Efficiencies [%]	Electric power	4.6	4.7	5.0	5.0	5.3	5.5	6.0	9.9	11.7	13.0
	Thermal power	2.8	11.7	12.5	12.3	10.3	12.5	11.7	16.8	26.5	29.0
	Electric efficiency	22.5	25.5	24.8	25.5	30.0	26.8	28.8	31.5	28.5	28.5
Fuel	Thermal efficiency	63.0	58.5	66.0	55.8	58.5	59.8	56.2	53.5	64.6	62.5
	PER	85.5	84.0	90.9	88.2	88.5	86.6	85.0	85.0	93.1	90.5
		Natural gas, LPG	Natural gas, LPG	Natural gas, propane	Natural gas, LPG	Biodiesel	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas
Weight [kg]	L	83	465	390	410	530	530	465	790	750	750
	H	580	1100	760	1100	720	720	1100	1470	1450	1250
	D	880	1500	1080	1500	1000	1000	1790	1200	1200	1110
Engine	No. Cyl.	380	660	1370	500	1060	1060	660	800	750	750
	Displ. [cm ³]	1	3	1	3	1	1	3	3	4	4
		163	952	270	699	579	579	952	1642	1600	2237
Generator	Inverter three phases		Inverter synchronous single phase	Asynchronous three phase	Single phase	Asynchronous three phase	Asynchronous three phase	Inverter synchronous single phase	Inverter three phase	Asynchronous three phase	Asynchronous three phase
	Noise [dBA]	44	54	56	56	58	56	54	54	53	49

Table 2

MCHP systems, based on Stirling engine, with their specification.

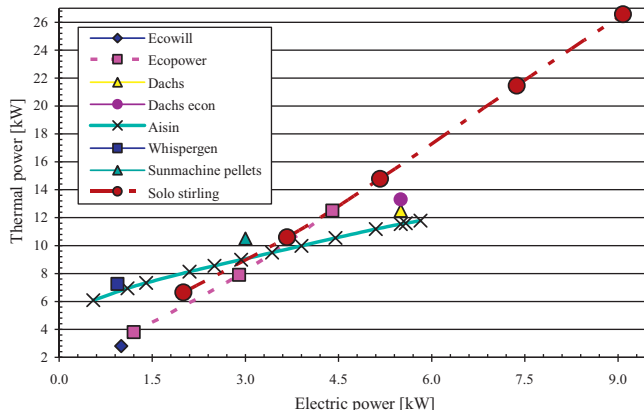
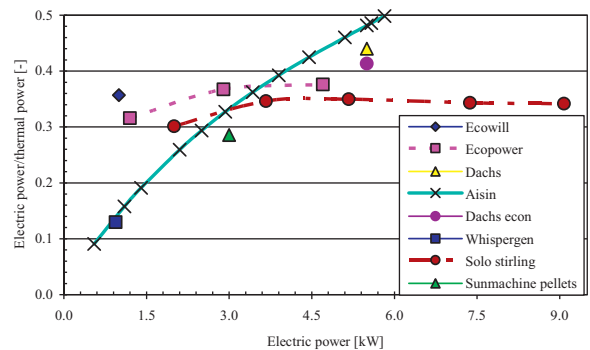
		1. Whispegen	2. BAXI Ecogen	3. HRE-boiler	4. Sunmachine	5. SM5A	6. Solo 161
Power [kW]	Input power	8.3	7.4	8.0	15.0	38.4	36.0
	Electric power	1.0	1.0	1.0	3.0	8.1	9.0
	Thermal power	7.0	6.0	6.4	10.5	24.9	26.0
Efficiencies [%]	Electric efficiency	12	13.5	12.5	20.0	21.1	25.0
	Thermal efficiency	84.3	81.1	80.0	70.0	64.8	72.2
	PER	96.3	94.6	92.5	90.0	85.9	97.2
Fuel		Natural gas	Natural gas, biogas	Natural gas, LPG	Wood pellet	Biogas	Natural gas, LPG, biogas, biomass
Weight [kg]		137	110		410	900	460
Dimensions [mm]	<i>L</i>	480	450		1160	650	1280
	<i>H</i>	840	950		1590	1505	980
	<i>D</i>	560	426		760	990	700
Engine	No. Cyl.	4			1	1	2
	Displ. [cm ³]				520	550	160
Working gas		Nitrogen			Nitrogen	Helium	Helium, hydrogen
Maximum pressure [bar]					36	80	150
Engine type		Alpha	Linear Free Piston	Linear Free Piston	Alpha	Beta	Alpha
Generator		Single phase				Asynchronous	three phase
Noise [dBA]			45				

They can work only at full load with ON-OFF regulation as shown in the following figures. Furthermore, the performance of Aisin at full load is slightly different in comparison with rated data due to self-consumption (200 W) of electric energy.

In Fig. 2 the thermal power trend at different supplied electric power is reported. The Aisin cogenerator works under a higher range of electric output (0.5–5.8 kW), typical of light commercial user, with a corresponding thermal power output in the range of 6.0–11.7 kW. Ecopower covers a smaller interval of electric power (1.3–4.7 kW) with a corresponding thermal power output in the range of 4.0–12.5 kW. Ecowill and Whispegen units are suitable for single family houses delivering about 1 kW of electric power. SOLO Stirling covers a large range of electric (2–9 kW) and thermal power (7–26 kW). Finally the manufacturer data of Sunmachine unit, that are different from data available from [28], in which a prototype and weakening version of the unit that works at partial load has been tested, are reported in Fig. 2 and thereafter.

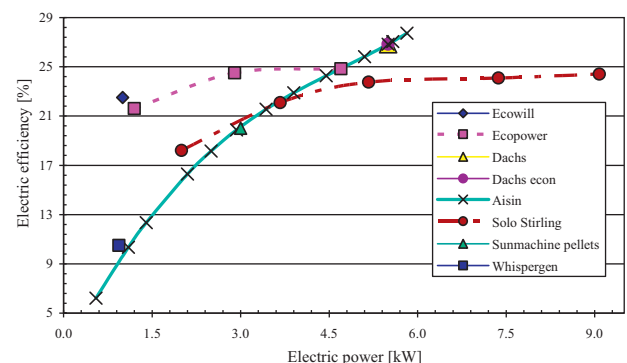
In Fig. 3, the ratio $\dot{E}_{el}/\dot{E}_{th}$, as a function of the electric power is shown. This ratio is usually adopted to match the end-user loads especially if it is not possible to sell electric energy surplus to the grid. This parameter increases with the electric output due to the η_{el} increase for Aisin while Ecopower and Solo show a trend that is almost constant.

For the MCHPs based on internal combustion engine, the measured values (0.1–0.5) are lower than those of large size cogenerators (0.9–1.0) based on the same engine ($\dot{E}_{el} > 0.1$ MW).

**Fig. 2.** Thermal power at different electric power supplied.**Fig. 3.** Ratio of electric power to thermal power vs. the supplied electric power.

It is very important to evaluate the electric efficiency of the microcogenerators under different working conditions. Fig. 4 shows the η_{el} , in accordance with the larger sized CHPs, increases with the $\dot{E}_{el}$, thereby stressing the need to use the MCHPs for large number of hours, at maximum load. Under the best conditions, Aisin and Dachs have an electric efficiency very close to 27%, comparable with the performances of larger size cogenerators ($30 \leq \eta_{el} \leq 40\%$). SOLO MCHP is characterized by a quasi constant electric efficiency in the range of 5–9 kW, guaranteeing good performance at partial load too.

In order to evaluate the global efficiency of the MCHP, it is interesting to evaluate the PER, Fig. 5, that is reported as a function of the electric output.

**Fig. 4.** Electric efficiency vs. the supplied electric power.

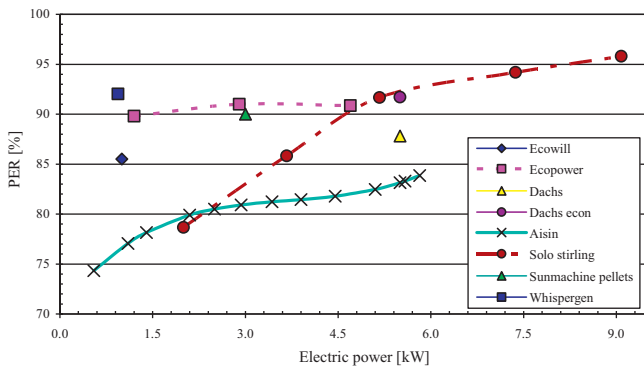


Fig. 5. PER vs. the supplied electric power.

In particular PER increases with the electric power. Ecopower and Dachs with economizer show, with regards to RIC engine, the best results in the whole range of operating conditions with a PER higher than 90%. The PER performed by Aisin, ranging between 73% and 84% under test conditions is in good agreement with the nominal value (PER about 85%). Stirling-based MCHPs show satisfactory results: SOLO reaches the best performance with a PER higher than 95%, while Whispergen and Sunmachine have a PER equal to 83% and 90% respectively. The performance of Sunmachine model is not satisfactory with a PER of about 70%, if the experimental data reported in [28] are considered. In Fig. 6 the iso-PER curves, as a function of electric and thermal power delivered by Aisin MCHP, are reported. On this graph the best operating modes with respect to PER index can be identified. In fact if, for example, the electric power delivered by MCHP unit is 5.1 kW (see point A in Fig. 6) the maximum corresponding thermal power is about 11.2 kW: in this case the maximum PER is in the range 80–85%. If thermal power recovered by MCHP is partially wasted PER decreases: if thermal power required by end user is 9.5 kW (see point B) the PER decreases in the range 70–75%.

4. Comparison between the microcogenerators and the reference system

Going by the data available on scientific literature the Energy, Economic and Environmental implications (3-E analysis), due to the use of these small scale cogeneration systems, have been reported. With this approach the performances of the Alternative System, AS, in this case a MCHP, are compared to those of the Conventional energy System, CS, based on separate “production”, in this case the power plant, PP, connected to the electric grid and a natural gas-fired Boiler, B. In Fig. 7, the energy flows are shown: alternative and conventional systems can satisfy both the electric power, $\dot{E}_{el,US}$, and the thermal power, $\dot{E}_{th,US}$, requirements for space heating

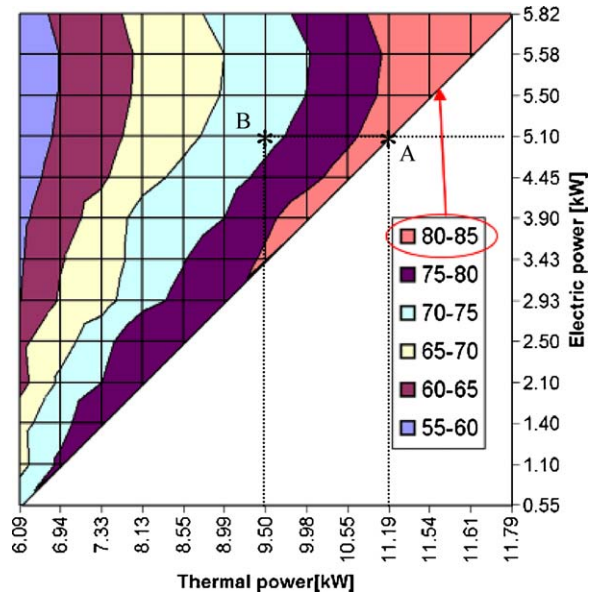


Fig. 6. Iso-PER curves of AISIN MCHP vs. the electric and thermal power.

and/or domestic hot water production. The conversion parameters and primary energy flows are also shown in the same figure.

For energy and environmental analysis, two parameters are commonly used: the primary energy saving (PES, Eq. (1)) and the equivalent CO₂ avoided emissions (ΔCO_2 , Eq. (2)), defined as follows:

$$\text{PES} = \frac{E_{p,CS} - E_{p,AS}}{E_{p,CS}} \quad (1)$$

$$\Delta\text{CO}_2 = \frac{\text{CO}_{2,CS} - \text{CO}_{2,AS}}{\text{CO}_{2,CS}} \quad (2)$$

$\text{CO}_{2,CS}$ and $\text{CO}_{2,AS}$ are carbon dioxide equivalent emissions of the conventional system and the alternative one. The efficiency reference values and CO₂ emission factor depend on the technology used to produce electricity and heat. Furthermore, with reference to the analysis of the potential diffusion of cogeneration in a geographic area, the mix of energy conversion systems adopted in that area must be considered. Therefore, as regards the Italian situation and legislation restraints for both alternative and conventional systems, the following hypotheses are assumed:

- Electric grid: efficiency $\eta_{el,PP} = 46.0\%$ (including transmission and distribution losses), CO₂ equivalent emission = 0.53 kgCO₂/kWh_{el} (“el” refers to the electrical energy supplied by the grid);

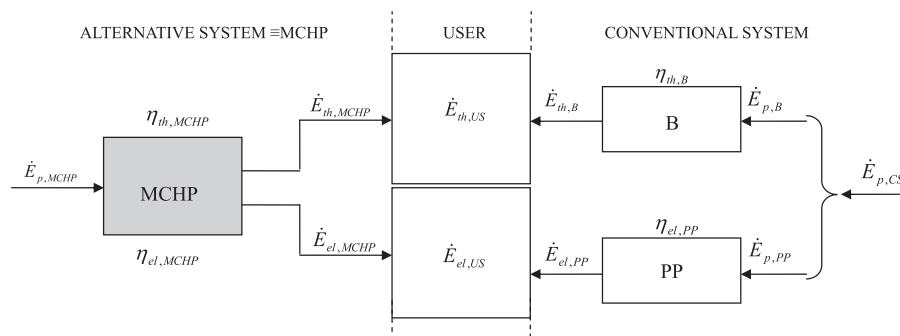


Fig. 7. Energy flows of alternative (MCHP) and conventional (power plant and boiler) systems.

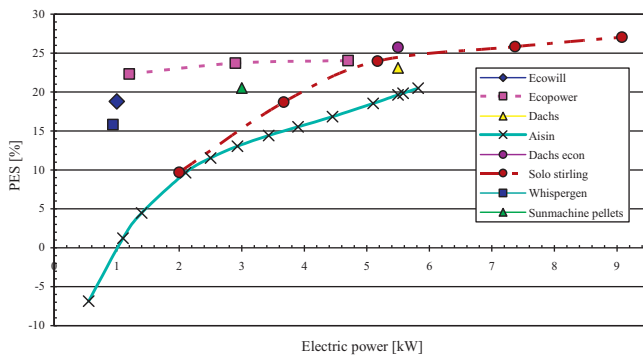


Fig. 8. PES vs. the supplied electric power with reference to Italy AS.

- Boiler: efficiency $\eta_{el,B} = 85.0\%$, CO_2 equivalent emission = $0.20 \text{ kgCO}_2/\text{kWh}_p$ ("p" refers to the primary energy input of the boiler);
 - LHV (lower heating value) of natural gas = $9.59 \text{ kWh}/\text{Nm}^3$.
- With respect to the German data, the electric reference efficiency value is 34.1% while the CO_2 emission factor is equal to 0.56 [30].

Using these efficiency values, considered as constant in all of the tested operative conditions, the PER of the conventional system is in the range 66–79%. From Fig. 8, which reports the comparison of AS with Italian CS, it is possible to remark that there is an energy saving ($\text{PES} > 0$) using Aisin for electric power values higher than 1 kW, and its maximum value is about 20%. The other RIC cogenerators guarantee satisfactory results with PES higher than 19% and a value of 26% for Dachs with economizer. The Stirling based PES varies between 10% and 27%.

In Fig. 9 the PES based on German AS that is higher than about 10% with respect to Italian AS is reported.

From Fig. 10, which reports the results of Italian AS, it is possible to remark that the CO_2 emissions are lower than the conventional system ($\Delta\text{CO}_2 > 0$) in almost the entire operating range. Under the best condition, at full load, MCHP systems allow for a reduction of greenhouse gas emissions between 19% and 33%. Comparable results, due to similar CO_2 emission factors, can be obtained considering the German AS.

In order to compare the MCHP units with other scenarios, different performance indices for conventional system have been considered. In particular, a range of electric efficiency that varies between 39%, typical of some European countries [31], and 53% that is typical of gas fuelled combined cycle power plant: with a corresponding CO_2 emission factors are 0.70 and $0.40 \text{ kgCO}_2/\text{kWh}_{el}$. With respect to the thermal efficiency, based on LHV of the fuel, the

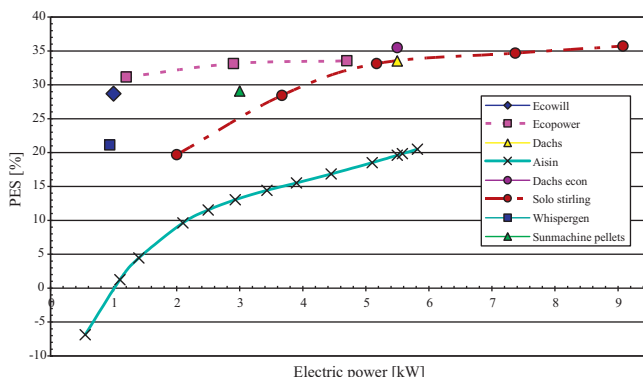


Fig. 9. PES vs. the supplied electric power with reference to Germany AS.

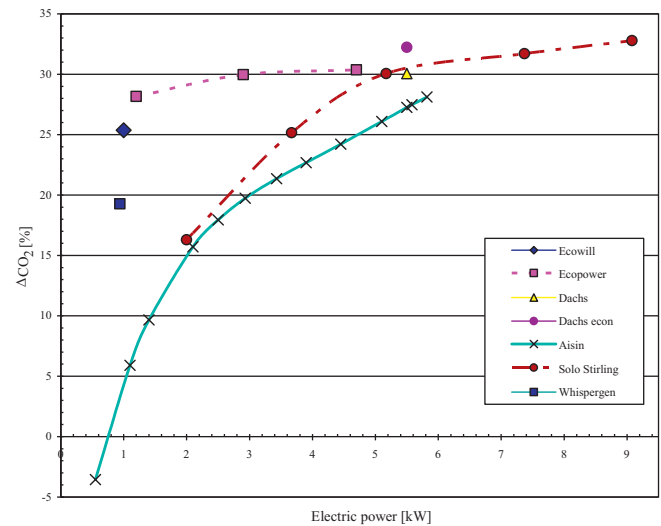


Fig. 10. ΔCO_2 trend vs. the supplied electric power with reference to Italy AS.

range 85–105% has been considered in order to take into account the performance of the gas-fired condensing boiler. In Fig. 11, the trend of PES, as a function of electric efficiency of power plant, considering as constant thermal efficiency of boiler ($\eta_B = 85\%$) is shown. Even if the CS is based on combined cycle gas turbine, the PES ranges in the interval 14–21%. In Fig. 12, the trend of PES, as a function of thermal efficiency of boiler, considering as constant electric efficiency of power plant ($\eta_{pp} = 46\%$) is shown. Even if the CS is based on gas-fired condensing boiler, the PES is positive and lower than 16%.

In Fig. 13, the PES of Ecowill, as a function of electric efficiency of PP and thermal efficiency of B, is reported. In the entire operating range, the PES is positive.

The ΔCO_2 is within the range 14–23%, Fig. 14, if the MCHPs are compared to the benchmark system for electric energy "production" ($\eta_{pp} = 53\%$).

In Fig. 15, ΔCO_2 is within the range 5–23% if the MCHPs are compared to a CS that presents the gas-fired condensing boiler system ($\eta_B = 105\%$) for thermal energy "production".

Finally if we take into account the best available and economically justifiable technologies for CS ($\eta_{pp} = 53\%$, $\eta_B = 105\%$), the PES and ΔCO_2 are positive, with the exception of Whispergen model, as shown in Table 3.

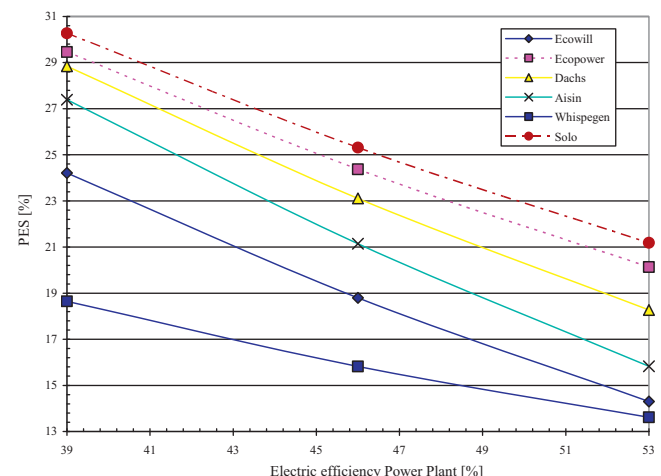


Fig. 11. PES vs. electric efficiency of power plant.

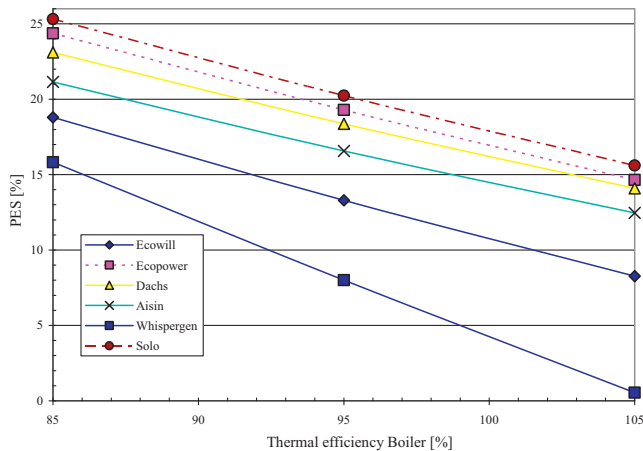


Fig. 12. PES vs. the thermal efficiency of the boiler of CS.

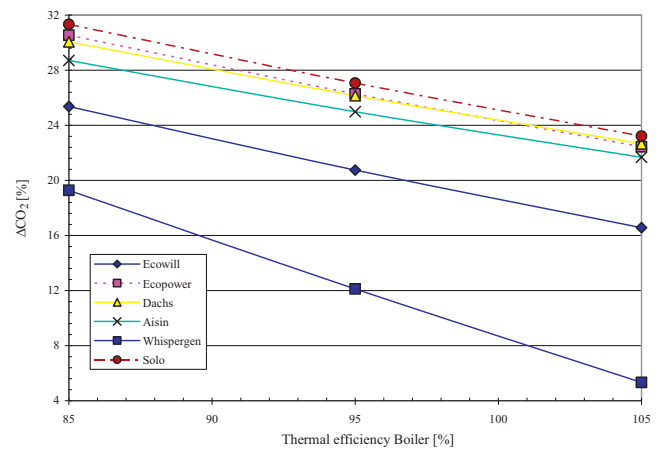


Fig. 15. ΔCO_2 trend vs. thermal efficiency of boiler.

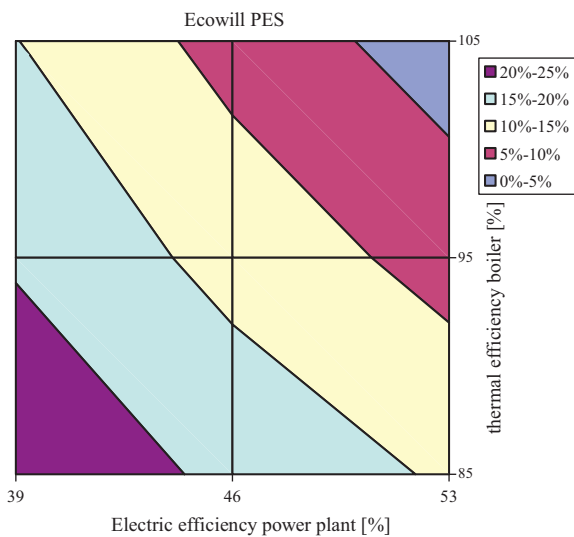


Fig. 13. PES vs. the thermal (η_B) and electric (η_{PP}) efficiency of CS.

The analysis of these values is important in order to support this technology which, in a brief period of time, could give benefits in terms of primary energy saving and reduction of polluter emissions. In fact, a massive use of this technology could contribute, in a very

strong way, to the emissions reduction and primary energy saving, according to European Union target by 2020.

The Commission of the European Communities [32], in agreement with Directive 2004/8/EC on the promotion of cogeneration, gives a method to evaluate the harmonised efficiency reference values for separate production of electricity and heat. In particular, the value of the electric reference efficiency is a function of the year of construction of a cogeneration unit, the climatic condition, the electricity used on-site and the avoided grid losses due to decentralised production.

With respect to the MCHPs considered, the evaluation of PES has been carried out under the following hypothesis:

- the total amount of electricity is used by end-user;
- the cogeneration units have been installed in 2010;
- the ambient temperature is 18 °C for Italy and 9 °C for Germany;
- the fuel is natural gas;
- low voltage (<400 V).

The reference efficiency values obtained are about 44.9% (Italy) and 45.1% (Germany) for electricity and 90% for boiler. If 50% of electricity produced by MCHP is used for own consumption and 50% is fed into the grid the reference electric efficiency values are about 46.6% (Italy) and 45.7% (Germany). PES, considering the above mentioned value for electric efficiency of CS, which are in good agreement with the typical value of the Italian mix, but are different from the German mix are reported in Table 4.

If MCHP electric power is less than 50 kW, the PES has to be higher than zero in order to recognize this system as a cogeneration system.

5. Economic analysis

Finally, to complete the analysis of small scale cogeneration, the evaluation of economic performance indices is necessary. In fact, a significant diffusion of CHP technology, characterized by energy

Table 3
PES and ΔCO_2 for BAT.

MCHP	PES [%]	ΔCO_2 [%]
Ecowill	2.5	4.9
Ecopower	9.2	11.4
Dachs	8.0	10.5
Aisin	5.8	8.6
Whispergen	−2.6	−1.3
Solo	10.3	12.5

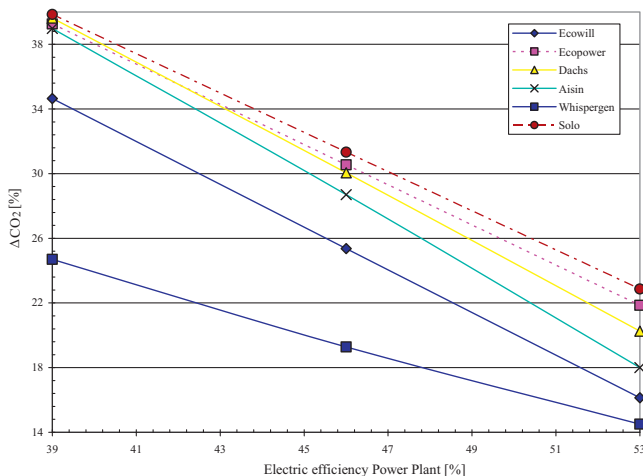
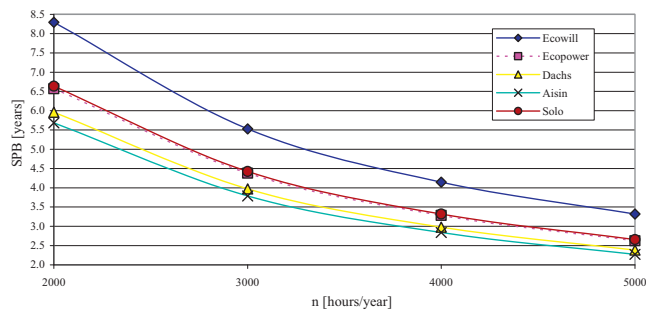


Fig. 14. ΔCO_2 trend vs. electric efficiency of power plant.

Table 4

PES as a function of reference electric efficiency as defined by Directive 2004/8/EC and subsequent ones.

MCHP	PES [%]			
	Italy, 100% electricity self-consumption	Italy, 50% electricity self-consumption	Germany, 100% electricity self-consumption	Germany, 50% electricity self-consumption
Ecowill	16.8	15.6	16.2	15.0
Ecopower	22.6	21.4	22.0	20.8
Dachs	21.6	20.2	20.9	19.6
Aisin	19.8	18.3	19.1	17.6
Whispergen	24.2	11.6	11.6	11.3
Solo	12.3	22.3	22.3	21.8

**Fig. 16.** SPB vs. operating hours per year of the MCHPs with regards to Italy.

and environmental advantages, requires an investment cost capable of guaranteeing a short payback period. However, the number of the parameters to consider does not permit to obtain homogeneous results depending, above all, on the different conditions in the various countries. Therefore, a lot of subjects are involved in the definition of the economic variables including the public and the private sectors (gas utilities, manufacturers, etc.). For example, the possibility of obtaining funds as well as selling the electric surplus to the grid at good price, could strongly contribute to CHP market penetration.

Subsequently however, in order to give general indications, the Simple Pay Back, SPB, of MCHPs will be evaluated at full electric load as a function of operating hours per year. The investment cost considered for the economic analysis has been estimated considering the European market costs [24,33], with the exception of Ecowill that is sold in Japan at €4200 (including a financial support from natural gas distribution companies). According to the Italian market, an electric energy price of €0.17/kWh and a natural gas price of €0.70/Nm³ have been assumed. In Fig. 16, the SPB, at different number of working hours per year, is shown. A reduction of the natural gas price for cogenerative use, which is inversely proportional to MCHP electric efficiency has been considered. This ranges between 0 and €0.22/Sm³ when electric efficiency is 45%. The maintenance cost for MCHP of €0.025/kWh_{el} has been considered too. The results seem to be very promising as it allows an acceptable SPB for more than 2500–3500 operating hours per year, with the exception of Whispergen MCHP that has an SPB of about 10 years considering 5000 operating hours per year.

To show the influence of some basic parameters on the profitability of MCHP systems, the parameters in Table 5 were chosen and some of them used for a sensitivity analysis. The data reflects the conditions as they occur in Germany today. For CHP systems with up to 50 kW of rated electric power, a subsidy of €0.051/kWh_{el} is given for the whole generated electricity, regardless of the fact that it is used within the building or fed into the electric grid. A sensitivity analysis was performed on Dachs cogenerator considering the reference data reported in Table 5 that guarantees an annual surplus of €402.

Table 5

Reference data considered in the sensitivity analysis.

Operating hours per year	h	4000
Share of own use	%	70
Investment cost	€	22,000
Lifetime	Years	20
Interest rate	%	5.0
Maintenance	% of investment	3.5
Gas price	€/Nm ³	0.450
Electricity price	€/kWh	0.190
Feed in tariff	€/kWh	0.050
CHP generation bonus	€/kWh	0.051
Annual balance	€/y	402

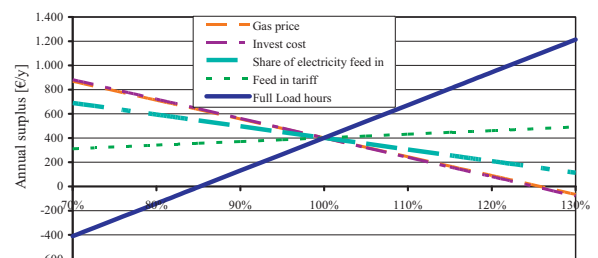
**Fig. 17.** Sensitivity analysis of annual economic balance.

Fig. 17 shows the sensitivity of annual economic surplus, with respect to a system based on separate “production” (boiler + grid), if some parameters, such as natural gas price, investment cost, feed in tariff, ..., are varied by ±30%. The most sensitive parameter depends on working hours per year: the more the system operates at full load, the better is the financial balance. If the MCHP system can work 5200 h per year, corresponding to an increase of 30% with respect to the reference case, the annual economic surplus reaches about €1200.

Investment costs and gas price have also a strong impact on the profitability of the system while the feed in tariff for electricity to the grid is of inferior relevance.

If the natural gas price or the investment cost increase up to 30% the annual economic surplus is negative, so in this case the MCHP system is not a good option, however, if the opposite doubles annual earnings.

Another parameter considered is the use of electricity (personal use and feed in the grid) available from MCHP by means of share of electricity feed in. This is due to German economic conditions for which avoided cost, due to personal use of electricity, is higher than the gain (feed in tariff and CHP generation bonus) obtained by delivering electricity to the grid. Therefore the choice of MCHP system, appropriate to the end user, is very important.

It is evident that the greatest obstacle to the diffusion of small size cogeneration is the investment cost, which is too high, in comparison to similar technologies developed for higher sizes.

6. Conclusions

In this paper, the possibility of the development of a small scale cogeneration has been analyzed by evaluating the Energy, Economic and Environmental impact implications (3-E approach). Attention has been paid to the use of this well-established technology that has been noted by European Union as one of the first elements to save primary energy and to reduce the greenhouse gas emissions, also for residential and light commercial users. An experimental analysis performed by authors and other researchers on different MCHP units, based on RIC and Stirling engine, have been reported. The most important energy, economic and environmental impact performance indices have been evaluated and compared to the same parameters of the conventional system for separate production of heat and electricity with respect to Italy and Germany. The results obtained are encouraging. In fact the micro-cogeneration already allows to obtain primary energy savings up to 27% (Italy) and 36% (Germany) and a pollutant emissions reduction up to 35% (Germany) and 33% (Italy). The MCHPs perform better, in terms of primary energy savings and avoided equivalent CO₂ emissions, than BAT for almost all the units. As regards the economic analysis, it is evident that the greatest obstacle to diffusion of small-scale cogeneration is its investment cost in comparison to similar technologies developed for higher sizes. It can be finally stated that the cogeneration represents a mature technology even in small size applications. MCHP units based on reciprocating internal combustion engine are at the moment available on the market. The MCHPs based on Stirling engine are not widely used. However, thanks to the advantages that characterize this technology, there is an increasing interest for its use in residential and light commercial applications. In EU countries (UK, Germany and Italy), Japan and U.S.A. economic actions to support this technology are encouraging diffusion of MCHP units [34].

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